# Chapter 8
# Turbomachines

During the 2nd century BC, Hero demonstrated the principle of a reaction turbine, but could not realize any useful work. Despite the scientific revolution followed by the industrial revolution, James Watt, while attempting to build a steam turbine, came to the conclusion that it could not be built given the state of contemporary technology.

About the year 1837 several reaction steam wheels were made by Avery at Syracuse, New York, and by Wilson at Greenock [3], for driving circular saws and cotton gins, see Figure 8.1. Steam was introduced into it through a hollow shaft, and, by the reaction of the jets at the extremities, caused rotation.

By the middle of the 19th century, there was a fair amount of understanding of the vibration characteristics of strings, beams, membranes and plates; however, nothing was known about a beam when it becomes a shaft and rotates. William John Macquorn Rankine (1820–1872) proposed in 1869 that a critical speed exists for a rotor which is the limit of speed for centrifugal whirling. It was not known whether a rotor can cross this limiting critical speed as Rankine proposed this as a limiting speed. Nearly two decades later in 1883 (about 100 years after Watt built his steam engine), De Laval of Stockholm undertook the problem with a considerable measure of success. Karl Gustaf Patrik de Laval (1845–1913) was a Swedish engineer and inventor who made important contributions to the design of steam turbines and dairy machinery. He built the first steam turbine (impulse turbine) [5], where high pressure steam was blown through nozzles whose inner shape "a" allowed the steam to expand to low pressure, see Figure 8.2. Its velocity was then greatly increased, and when the steam jets hit the turbine wheel's bent vanes "b", the wheel was set in motion. The slim, resilient turbine axle is mounted in its bearings 1 which were fixed in spherical segments 2 so that the axle could stand up to the whipping resonance vibrations.

Once a rotating machine was achieved with steam as motive force, there was a tremendous expansion in the capacity of power generation. Just one year after Laval's turbine, Charles Parsons [3] in 1884 came up with the first reaction turbine [5]. Sir Charles Algernon Parsons (1854–1931) was a British engineer, best known for his invention of the steam turbine (see Figure 8.3). Because of heavy vibrations

**Fig. 8.1** Rotor of Avery's turbine. (Courtesy Cambridge University Press)

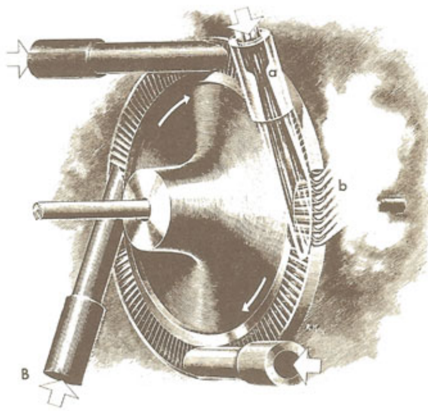


**Fig. 8.2** Laval's turbine and critical speed. (Courtesy Cambridge University Press)

in reciprocating machines with severe torque and speed fluctuations, these turbines are hailed "vibration free engines" for that time at least.

Laval was also able to derive the whirl radius $y$ in terms of shaft eccentricity $\delta$, shaft stiffness $F$ and weight $W$ and explain how the rotor rotates smoothly beyond the critical speed, which Rankine thought 14 years ago that the critical speed is the limiting speed. These are the benefits from the Science revolution to speed up the industrial revolution.

With the invention of Dynamo in 1878 by Thomas Alva Edison and installation of Pearl Street Electric Power Station in 1882 (see Figure 8.4), the path has been cleared to produce electricity in an unprecedented scale which brought in a phenomenal expansion of the steam turbine; the early part of 20th century has seen 2 MW turbines, by 1920 the first 50 MW machine was made and by end of the II World War, 100 MW machines began to produce power. The capacity rose to 1000 MW by 1970 and in 1980 a single machine produced 1500 MW electricity (see Figure 8.5), see GE Steam Turbines, and *A Century of Progress* [1].

Heinkel He-178 was the world's first turbojet-powered aircraft in 1939, flying nearly two years before the British Gloster E28. It was powered by propellerless engine, a jet engine or gas turbine rather than a piston engine. Hans von Ohain (1911–1998) studied at University of Göttingen and when 22 years old he first conceived the idea of a continuous cycle combustion engine in 1933; he patented a jet propulsion engine design similar in concept to that of Frank Whittle (1907–1996) but different in internal arrangement in 1934. After receiving his degree in 1935, Ohain became the junior assistant of Robert Wichard Pohl, then director of the

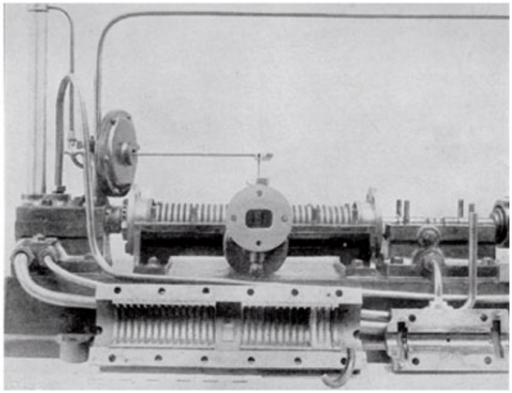

**Fig. 8.3** First Parson's turbine. (Courtesy Cambridge University Press)

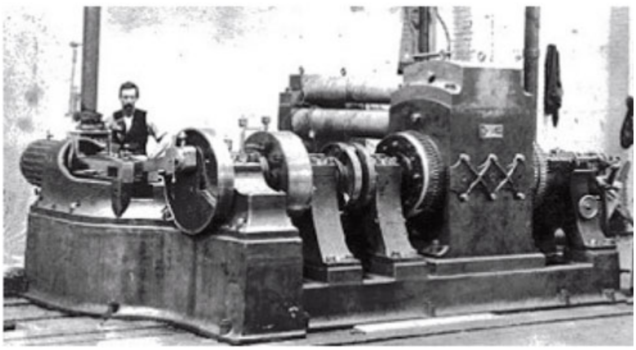

**Fig. 8.4** Edison's Jumbo Dynamo – a 27-ton machine that produced 100 kilowatts at Pearl Street Electric Power Station. (Courtesy Thomas Edison National Historical Park)

Physical Institute of the University. Hans von Ohain and Frank Whittle are both recognized as being the co-inventors of the jet engine. Each worked separately and knew nothing of the other's work. While Hans von Ohain is considered the designer of the first operational turbojet engine, Frank Whittle was the first to register a patent for the turbojet engine in 1930. Hans von Ohain was granted a patent for his turbojet engine later in 1936 [2]; however, Hans von Ohain's jet was the first to fly in 1939. Frank Whittle's jet first flew in 1941.

While working at the University, von Ohain met an automotive engineer, Max Hahn, and eventually arranged for him to build a model of his engine. When it was complete he took it to the University for testing, but ran into serious problems with combustion stability. Often the fuel would not burn inside the flame cans, and would instead be blown through the turbine where it would ignite in the air, shooting flames out the back and overheating the electric motor powering the compressor.

In February 1936, Pohl wrote to Ernst Heinkel telling him of the von Ohain design and its possibilities. Heinkel arranged a meeting where his engineers were

**Fig. 8.5** GE's N series steam turbines for nuclear applications up to 1500 MW. (From Steam Brochure GE Energy, 4200 Wildwood Parkway, Atlanta, GA 30339)

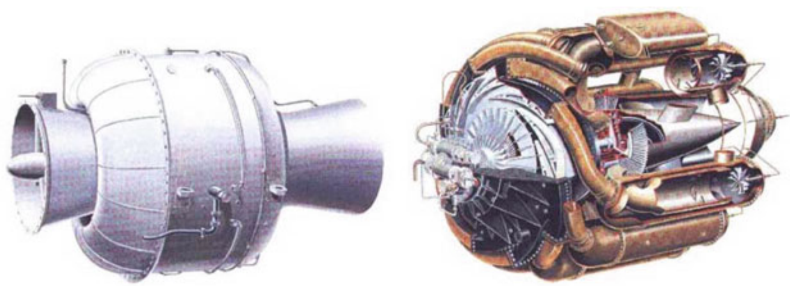

**Fig. 8.6** Hans Von Ohain first jet engine (left) and Frank Whittle's jet engine (right)

able to grill von Ohain for hours, during which he flatly stated that the current "garage engine" would never work but there was nothing wrong with the concept as a whole. The engineers were convinced, and in April, von Ohain and Hahn were set up at Heinkel's works at the Marienehe airfield outside Rostock, Germany in Warnemünde.

Once moved, a study was made of the airflow in the engine, and several improvements made over a two month period. Much happier with the results, they decided to produce a completely new engine incorporating all of these changes, running on hydrogen gas. The resulting Heinkel-Strahltriebwerk 1 (HeS 1), German for Heinkel Jet Engine 1 (see Figure 8.6), was built by hand-picking some of the best machinists in the company, much to the chagrin of the shop-floor supervisors. Hahn, meanwhile, worked on the combustion problem, an area he had some experience in.

Frank Whittle was a Royal Air Force Officer, proposed in a thesis that planes would need to fly at high altitudes, where air resistance is much lower, in order to achieve long ranges and high speeds [6]. Piston engines and propellers were unsuitable for this purpose, so he concluded that rocket propulsion or gas turbines driving propellers would be required: jet propulsion was not in his thinking at this stage. In 1929, Whittle had considered using a fan enclosed in the fuselage to generate a fast

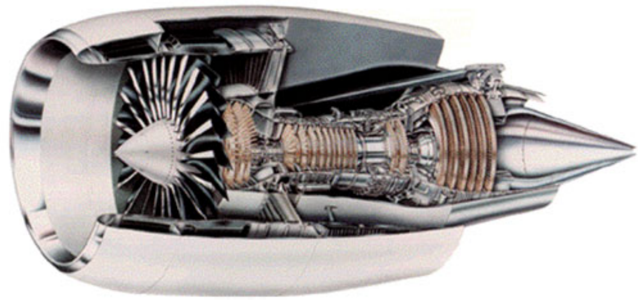

**Fig. 8.7** GE 90 Aircraft Engine produced a record thrust of 120,316 pounds in 2001, 75 times that of W.2 in 1941. (Courtesy Dino of Turbokart)

flow of air to propel a plane at high altitude. A piston engine would use too much fuel, so he thought of using a gas turbine and patented his idea.

In 1935 Whittle secured financial backing and, with RAF approval, Power Jets Ltd was formed. They began constructing a test engine in July 1936, but it proved inconclusive. Whittle concluded that a complete rebuild was required, but lacked the necessary finances. Protracted negotiations with the Air Ministry followed and the project was secured in 1940. By April 1941 the engine W.2 (see Figure 8.6) was ready for tests and it produced 1600 lb thrust. The first flight Gloster E.28/39 took place on 15 May 1941. By October the Americans had heard of the project and asked for the details and an engine. A Power Jets team and the engine were flown to Washington to enable General Electric examine it and begin construction. The Americans worked quickly and their XP-59A Aircomet was airborne in October 1942, some time before the British Meteor, which became operational in 1944.

In just six decades later, the General Electric GE-90 115-B engine (see Figure 8.7) is designed for a thrust rating of 115,000 pounds (511 kN), making it the most powerful jet engine in the world [4]. It is produced by a tight-knit partnership of General Electric, Snecma Moteurs, FiatAvio and IHI, and is intended for Boeing's new longer-haul 777 versions, the 777-200LR (Long Range) and the 777-300ER (Extended Range).

Rolls-Royce developed its first three-shaft engine, the RB211, in the late 1960s/early 1970s for the Lockheed TriStar. It went on to power the Boeing 747 jumbo jet, Boeing 757 and Boeing 767 (see Figure 8.8). The Industrial version of the RB211 entered service in 1972.

There have been several challenges in the development of high speed rotating machinery, steam turbines, gas turbines, and radial and axial flow compressors, internal or external combustors the key elements that go in making the complete drive units during the 20th century. While slow speed machinery could be developed by design methodologies, with high-speed complex machinery precise estimation of several important state quantities are necessary to be determined.

When it came to development the first gas turbine, Frank Whittle faced immense challenges; we will mention a few here:

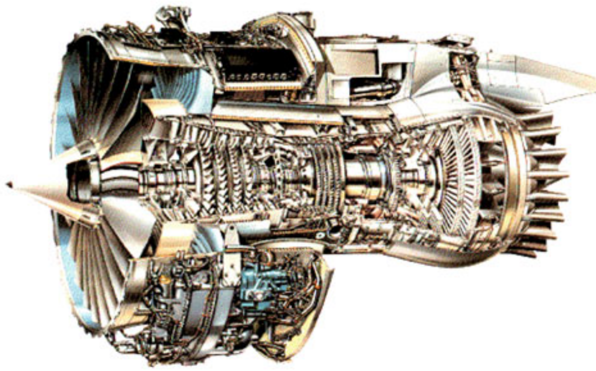

**Fig. 8.8** Rolls Royce RB211-524 turbofan engine

- January 16, 1930 filed for a patent based on the principle of using a gas turbine for propulsion.
- October to December 1936 conducted several combustion experiments and detailed design was ready by end of 1936.
- First engine W.U. with a single combustor was tested on April 12, 1937; when the speed was raised from 2000 to 2500 RPM, the engine suddenly ran away; the problems were attributed to fuel system. Suspended tests August 23, 1937.
- New combustion tests October 22, 1937; throughout the rest of 1937 combustion testing and the first rebuild of the engine, W.U.
- April 29, 1938 the engine ran for 1 hour 45 minutes before failure attaining a thrust of 480 pounds at 13,000 RPM. Failure attributed to rubbing of the turbine nozzle assembly with the turbine wheel at high speed, causing severe overheating and failure of the turbine blades (even to day almost seven decades later turbine blade vibration failures is a dreaded phenomena for the designer and maintenance man).
- Whittle abandoned the single combustor for a series of ten small combustion chambers; May 30, 1938 reconstructed the experimental engine for a second time.
- July 19, 1938, Whittle's team concluded that the feasibility of jet propulsion for aircraft has been experimentally established for the first time; at 73.3% design speed quantitative verification of the engine has been obtained.
- October 26, 1938 testing on the third rebuild of the experimental engine.
- March 1939 14000 rpm maximum speed achieved; a turbine blade failure caused a two month delay.
- June 17, 1939 testing resumed with a new impeller; it had 29 blades instead of 30 to avoid resonant coupling with the 10 blade diffuser system; June 26 16000 rpm was reached.
- On February 22, 1941, the third rebuild was destroyed by a turbine failure after a total running of 170 hours.

**Table 8.1** Significant events in the history of rotating machines

| Year | Significant Event |
|---|---|
| 2000000 BC | Beginning of Paleolithic or Old Stone Age – Dark Ages |
| 13000 BC | Beginning of Mesolithic or Middle Stone Age - Earliest movement achieved to pull and push under log rollers |
| 8000 BC | Beginning of Neolithic or New Stone Age – Agricultural villages |
| 6000 BC | End of Stone Age – Pottery and pottery wheel |
| 3000 BC | Wheel for transportation; sail ships |
| 250 BC | Archimedes |
| 200 BC | Hero's Aelopile – First reaction turbine |
| 31 BC | Vitruvius and water wheel |
| 700 AD | Wind mills |
| 1543 AD | Copernicus and Scientific Revolution |
| 1680 AD | Newton; Otto von Guericke |
| 1690 AD | Papin; Savery; Newcomen |
| 1750 AD | Euler |
| 1780 AD | James Watt and Industrial Revolution |
| 1883 AD | Laval and Parsons |
| | Edison, Pearl Street Station |
| 1940 AD | Von Ohain and Frank Whittle |
| 1980 AD | 1500 MW steam turbine, cryogenic pumps accelerating to 100000 RPM in 4–5 seconds |

- May 1941 the first engine shipped to Gloster and on 15th E28/39 took the flight for the first time.

Subsequently in May 1942, Whittle felt that the Ministry of Aircraft Production felt uneasy of the project as a whole and was in response to previous industry over-optimism; frequency of turbine blade failures was becoming the latest technological barrier to overcome. Rotors with mounted rotating parts continue to be the most stressed mechanical elements of all machinery and receive maximum attention in their design.

As a recap, the most significant events in the history of rotating machines are presented in Table 8.1.

It was almost two million years of existence of humans that can be described as Stone Age; the use of stone tools and the ability to walk straight up has set us apart from animal kingdom. Around 15000 years ago, the first breakthrough came in the Stone Age where man has learnt a faster way of moving things by inventing the sledge and roller. Though we are still dependent on human labor, the first step has been taken and ushered us into the Middle Stone Age from Old Stone Age. It is about 10000 years ago, we have settled down to live in a village rather than being totally nomadic and ushering in the New Stone Age. It took another 2000 years to invent the first wheel – pottery wheel for manufacturing applications. With this we have now learnt the ability to shape our own tools and the Stone Age has ended.

It is about 5000 years ago, we have transformed the log and pottery wheel to a wheel in transportation; bullocks and horses are used and we learnt to use animals extensively and replacing human work. Thus we began a new revolution with animal

power to satisfy the growing human needs. Relieved from human labor for existence, we found that extra time to think about our surroundings; understanding physics, chemistry and biology – for example we postulated that the universe is made of five elements.

We began to notice that animal power relieved us from drudgery but it is not fast enough to deliver the human dreams and vision for energy. 2200 years ago we began new experimentation with Archimedean knowledge base; Hero made initial attempts to harness steam energy through a turbine. Subsequently, hydro energy began to be exploited in the form of water wheels; wind energy was exploited in the form of wind mills. No major breakthroughs came as we were shackled by religion and remained earth centric in our thinking. The first jolt came in 1543 AD, merely 450 years ago when we discovered that we are at the universe center and our understanding on earth and its position in the universe is totally wrong. It took us another 120 years, to understand basic laws of motion of bodies, a prerequisite to properly postulate motion and design machinery in a scientific manner. We have just about three centuries of knowledge base in our existence of more than two million years. We learnt around this time that atmosphere around us exerts pressure that can be utilized to derive motion of a body instead of using animal power. A century later we discovered that steam pressure can be used directly to give us more and efficient power rather than vacuum principles; this helped us in developing reciprocating steam engines on a firm footing and exploit the energy for our industrial needs; a rapid expansion took place ushering in Industrial Revolution. Reciprocating machines are not ideal for generating powers at the level that we are able to conceive our imagination so far and the dream of Hero in developing a rotating machine could be achieved only in the late 19th century. Tremendous strides in technology were made in the 20th century to improve the rotating machinery to the present day status in Power, Transportation, Oil and Gas, Space industries.

Looking at the history of rotating machinery, we might think that we now know a lot about them; it is probably right to say that we do not know still a lot about them and imagine what is in store for us in the next 100 years. We will now study the evolution of rotor dynamic analysis methods in 20th century in the next coming chapters.

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